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Conservation Agriculture: Global Environmental Benefits of Soil Carbon Management

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Summary

Agricultural carbon (C) sequestration may be one of the most cost-effective ways to slow processes of global warming. Numerous environmental benefits may result from agricultural activities that sequester soil C and contribute to environmental security. As part of no-regret strategies, practices that sequester soil C help reduce soil erosion and improve water quality, and are consistent with more sustainable and less chemically dependent agriculture. While we learn more about soil C storage and its central role in direct environmental benefits, we must understand the secondary environmental benefits and what they mean to production agriculture. Increasing soil C storage can increase infiltration, fertility and nutrient cycling, decrease wind and water erosion, minimise compaction, enhance water quality, decrease C emissions, impede pesticide movement and generally enhance environmental quality. The sum of each individual benefit adds to a total package with major significance on a global scale. Incorporating C storage in conservation planning demonstrates concern for our global resources and presents a positive role for soil C that will have a major impact on our future quality of life.

Key words

soil organic matter, soil quality, environmental quality, conservation tillage, zero tillage, direct seeding, carbon sequestration

Introduction

Conservation agriculture (CA) aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. CA contributes to global environmental conservation as well as to enhanced and sustained agricultural production and can play a central role in global agricultural policy. Food security and sustainability are important for all citizens. Agriculture, the major industry for food and fibre production, is known to cause emission and storage of greenhouse gases. Intensification of agricultural production has been an important factor influencing greenhouse gas emission. Agricultural activities contribute to carbon dioxide (CO_2) emissions to the atmosphere through the combustion of fossil fuel, soil organic matter (SOM) decomposition and biomass burning. Improved conservation agricultural practices have great potential to increase soil carbon (C) sequestration and decrease net emissions of CO_2 and other greenhouse gases that contribute to global environmental security.

World soils are an important pool of active C and play a major role in the global C cycle and have contributed to changes in the concentration of greenhouse gases in the atmosphere. Agriculture is believed to cause some environmental problems, especially related to water contamination, soil erosion and greenhouse effect (Houghton *et al.*, 1999; Schlesinger 1985; Davidson and Ackerman, 1993). The soil contains two to three times as much C as the atmosphere. In the last 120 years, intensive agriculture has caused a C loss between 30 and 50%. By minimising the increase in ambient CO_2 concentration through soil C management, we minimise the production of greenhouse gases and minimise potential for climate change. Recent results suggest scientific agriculture can also lessen environmental problems and mitigate the greenhouse effect. In fact, agricultural practices have the potential to store more C in the soil than farming emits through land use change and fossil fuel combustion (Lal *et al.*, 1998).

Soil quality is the fundamental foundation of environmental quality. Soil quality is largely governed by SOM content, which is dynamic and responds effectively to changes in soil management, primarily tillage and C input. This review will primarily address soil C and its associated environmental benefits. Other recent reviews on the role of C sequestration in CA were presented by Robert (2001), Uri (1999), Tebrugge and Guring (1999), Lal *et al.* (1998) and Lal (2000). Agriculture has an opportunity to offset some CO_2 emissions and will be a small but significant player in sequestering carbon.

Key role of soil organic matter

Soil organic C represents a key indicator for soil quality, both for agricultural functions (production and economy) and for environmental functions (C sequestration and air quality). Soil organic matter is the main determinant of biological activity because it is the primary energy source. The amount, diversity and activity of soil fauna and micro-organisms are directly related to SOM content and quality. Organic matter and the biological activity that it generates have a major influence on the physical and chemical properties of the soils. Soil aggregation and stability of soil structure increases with increasing organic C. These factors in turn increase the infiltration rate and available water holding capacity of the soil as well as resistance to erosion by wind and water. Soil organic matter also improves the dynamics and bio-availability of main plant nutrient elements.

Soils contain relatively small amounts of C that could be considered analogous to a catalyst for biological activity, where a small amount has a big impact. Farmers are the primary soil managers who all have a tremendous responsibility to maintain SOM for environmental benefit of the global population. Thus, farmers who use CA or direct seeding techniques are providing ecosystem services and helping to maintain environmental quality for all of society. Quality food production, and economic and environmentally-friendly management practices that are socially acceptable, will lead to sustainable production and be mutually beneficial to farmers and all others in society. It is important, therefore, that C loss from the soil system through historical land use of farming practices be restored to its natural potential using direct seeding and conservation tillage methods for sustainable production.

Sources and sinks in agricultural systems

Agricultural systems contribute to C emissions through several mechanisms including direct use of fossil fuels in farm operations, indirect use of energy inputs for manufacturing chemicals (typically fertilisers), irrigation and grain drying, and through intensive tillage of soils resulting in the loss of SOM. With CA techniques, soils can accumulate C to offset other C losses. Thus, the soil can be converted from a "source" of C to a "sink" for C with improved soil and crop management.

Preliminary assessments indicate that soil C sequestration can be a tool to offset C emissions from burning fossil fuels. We in agriculture play a significant role because of the large amount of soil C in the C cycle within agricultural production systems. The limited use of crop rotations combined with intensive tillage decreases soil quality and soil organic matter. Any operation that removes or incorporates crop residue contributes to the decline of soil C through increased biological oxidation. The drive to maximise profit in food and fibre production has created environmental problems that have slowly crept up on conventional agriculture and now requires new knowledge, research and innovation to overcome these concerns.

A case for Conservation Agriculture and zero tillage

Tillage or soil preparation has been an integral part of traditional agricultural production. Tillage is also a principal agent resulting in soil perturbation and subsequent modification of the soil structure with soil degradation. Intensive tillage loosens soil, enhances the release of soil nutrients for crop growth, kills the weeds that compete with crop plants for water and nutrients, and modifies the circulation of water and air within the soil. Intensive tillage can adversely affect soil structure and cause excessive breakdown of aggregates leading to potential soil movement via erosion. Intensive tillage causes soil degradation through C loss and tillage-induced greenhouse gas emissions that impact on productive capacity and environmental quality.

Recent studies involving a dynamic chamber, various tillage methods and associated incorporation of residue in the field indicated major C losses immediately following intensive tillage (Reicosky and Lindstrom, 1993; 1995). The mouldboard plough had the roughest soil surface, the highest initial CO_2 flux and maintained the highest flux throughout the 19-day study. High initial CO_2 fluxes were more closely related to the depth of soil disturbance that resulted in a rougher surface and larger voids than to residue incorporation. Lower CO_2 fluxes were caused by tillage associated with low soil disturbance and small voids with no-till having the least amount of CO_2 loss during 19 days. The large gaseous losses of soil C following mouldboard ploughing compared to relatively small losses with direct seeding (no-till) have shown why crop production systems using mouldboard ploughing have decreased SOM and why no-till or direct seeding crop production systems are stopping or reversing that trend. The short-term cumulative CO_2 loss was related to the soil volume disturbed by the tillage tools. This concept was explored when Reicosky (1998) determined the impact of strip tillage methods on CO_2 loss after five different strip tillage tools and no-till. The highest CO_2 fluxes were from the mouldboard plough and subsoil shank tillage. Fluxes from both slowly declined as the soil dried. The least CO_2 flux was measured from the no-till treatment. The other forms of strip tillage were intermediate with only a small amount of CO_2 detected immediately after the tillage operation. These results suggested that the CO_2 fluxes appeared to be directly and linearly related to the volume of soil disturbed. Intensive tillage fractured a larger depth and volume of soil, and increased aggregate surface area available for gas exchange that contributed to the vertical gas flux. That the narrower and shallower soil disturbance caused less CO_2 loss suggests that the volume of soil disturbed must be minimised to reduce C loss and impact on soil and air quality. The results suggest environmental benefits and C storage of strip tillage over broad area tillage that need to be considered in soil management decisions.

Reicosky (1997) reported that average short-term C loss from four conservation tillage tools was 31% of the CO_2 from the mouldboard plough. The mouldboard plough lost 13.8

times more CO_2 than the soil not tilled while conservation tillage tools averaged about 4.3 times more CO_2 loss. The smaller CO_2 loss from conservation tillage tools was significant and suggests progress in equipment development for enhanced soil C management. Conservation tillage reduces the extent, frequency and magnitude of mechanical disturbance caused by the mouldboard plough and reduces the large air-filled soil pores to slow the rate of gas exchange and C oxidation.

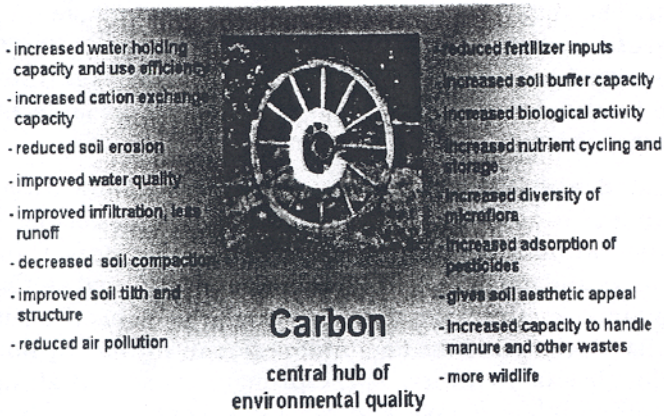
Carbon loss associated with intensive tillage is also associated with soil erosion and degradation that can lead to increased soil variability and yield decline. Tillage erosion or tillage-induced translocation, the net movement of soil down slope through the action of mechanical implements and gravity forces acting on the loosened soil has been observed for many years. Papendick *et al.* (1983) reported original topsoil on most hilltops had been removed by tillage erosion in the Paulouse region of the Pacific northwest of the US. The mouldboard plough was identified as the primary cause, but all tillage implements will contribute to this problem (Grovers *et al.*, 1994; Lobb and Kachanoski, 1999). Soil translocation from mouldboard plough tillage can be greater than soil loss tolerance levels (Lindstrom, Nelson and Schumacher, 1992; Grovers *et al.*, 1994; Lobb, Kachanoski and Miller, 1995; Poesen *et al.*, 1997). Soil is not directly lost from the fields by tillage translocation, rather it is moved away from the convex slopes and deposited on concave slope positions. Lindstrom *et al.* (1992) showed that soil movement on a convex slope in southwestern Minnesota, USA, could result in a sustained soil loss level of approximately 30 tonnes per hectare per year (t/ha/yr) from annual mouldboard ploughing. Lobb *et al.* (1995) estimated soil loss in southwestern Ontario, Canada, from a shoulder position to be 54 t/ha/yr from a tillage sequence of mouldboard ploughing, tandem disk and a C-tine cultivator. In this case, tillage erosion, as estimated through resident Cesium137, accounted for at least 70% of the total soil loss. The net effect of soil translocation from the combined effects of tillage and water erosion is an increase in spatial variability of crop yield and a likely decline in soil C related to lower soil productivity (Schumacher *et al.*, 1999).

Environmental benefits of soil carbon

The main direct benefit of CA or direct seeding is the immediate impact on SOM and soil C interactions. Soil organic matter is so valuable for what it does in soil that it can be referred to as "black gold" because of its vital role in physical, chemical and biological properties and processes within the soil system. Agricultural policies are needed to encourage farmers to improve soil quality by storing C that will also lead to enhanced air quality, water quality and increased productivity as well as to help mitigate the greenhouse effect. Soil C is one of our most valuable resources and may serve as a "second crop" if global C trading systems become a reality. While technical discussions related to C trading are continuing, there are several other secondary benefits of soil C impacting environmental quality that should be considered to maintain a balance between economic and environmental factors.

Soil C is so important that it can be compared to the central hub of a wheel as shown in Figure 1. The wheel represents a circle, which is a symbol of strength, unity and progress. The spokes of this wagon wheel represent incremental links to soil C that lead to the environmental improvement that supports total soil resource sustainability. Many spokes make a stronger wheel. Each of the secondary benefits that emanate from soil C contributes to environmental enhancement through improved soil C management. Soane (1990) discussed several practical aspects of soil C important in soil management. Some of the spokes of the environmental sustainability wheel are described in following paragraphs.

Figure 1: **Environmental sustainability wheel with benefits emanating from the soil C hub**



Increased SOM has a tremendous effect on soil water management because it increases infiltration and the water-holding capacity. The primary role of SOM in reducing soil erodibility is by stabilising the surface aggregates through reduced crust formation and surface sealing, which increases infiltration (Le Bissonnais, 1990). Enhanced soil water-holding capacity is a result of increased SOM that more readily absorbs water and releases it slowly over the season to minimise the impacts of short-term drought. In fact, certain types of SOM can hold up to 20 times their weight in water. Hudson (1994) showed that for each one per cent increase in SOM, the available water holding capacity in the soil increased by 3.7% of the soil volume. The extra SOM prevents drying and improves water retention properties of sandy soils. In all texture groups, as SOM content increased from 0.5 to 3%, available water capacity of the soil more than doubled. Other factors being equal, soils containing more organic matter can retain more water from each rainfall event and make more of it available to plants. This result plus the increased infiltration with higher organic matter and the decreased evaporation with crop residues on the soil surface all contribute to improving water use efficiency.

Ion adsorption or exchange is one of the most significant nutrient cycling functions of soils. Cation exchange capacity (CEC) is the quantity of exchange sites that can absorb and release nutrient cations. Soil organic matter can increase CEC of the soil from 20 to 70% over that of the clay minerals and metal oxides present. In fact, Crovetto (1996) showed that the contribution of the organic matter to the cation exchange capacity exceeded that of the kaolinite clay mineral in the surface 5 cm of his soils. Robert (2001) showed a strong linear relationship between organic C and CEC of his experimental soil. The CEC increased four-fold with an organic C increase from 1 to 4%. The toxicity of other elements can be inhibited by SOM which has the ability to adsorb soluble chemicals. The adsorption by clay minerals and SOM is an important means by which plant nutrients are retained in crop rooting zones.

Soils relatively high in C, particularly with crop residues on the soil surface, are very effective in increasing SOM and in reducing soil erosion loss. Reducing or eliminating runoff that carries sediment from fields to rivers and streams will enhance environmental quality. Under these situations, the crop residue acts as tiny dams that slow down the water runoff from the field allowing the water more time to soak into the soil. Worm channels, macropores and plant root holes left intact increase infiltration (Edwards *et al.*, 1988). Water infiltration is two to ten times faster in soils with earthworms than in soils without earthworms (Lee, 1985). Soil organic matter contributes to soil particle aggregation that makes it easier for the water to move through the soil and enables the plants to use less energy to establish root systems (Chaney and Swift, 1984). Intensive tillage breaks up soil aggregates and results in a dense soil making it more difficult for the plants to get nutrients and water required for their growth and production.

The reduction in soil erosion leads to enhanced surface and ground water quality, another secondary benefit of higher SOM (Uri, 1999). Crop residues on the surface help hold soil particles in place and keep associated nutrients and pesticides on the field. The surface layer of organic matter minimises herbicide runoff and, with conservation tillage, herbicide leaching can be reduced as much as half (Braverman *et al.*, 1990). The enhancements of surface and ground water quality are accrued through the use of conservation tillage and by increasing SOM. Increasing SOM and maintaining crop residues on the surface reduces wind erosion (Skidmore *et al.*, 1979). Depending on the quantity of crop residues left on the soil surface, soil erosion can be reduced to nearly nothing as compared to the unprotected, intensively tilled field.

Another key factor is SOM that can decrease soil compaction (Angers and Simard, 1986; Avnimelech and Cohen, 1988). Soane (1990) presented different mechanisms where soil "compactibility" can be decreased by increased SOM content: 1) improved internal and external binding of soil aggregates; 2) increased soil elasticity and rebounding capabilities; 3) dilution effect of reduced bulk density due to mixing organic residues with the soil matrix; 4) temporary or permanent existence of root networks; 5) localised change in electrical charge of soil particle surfaces, 6) change in soil internal friction. While most soil compaction occurs during the first vehicle trip over the tilled field, reduced weight and horsepower requirements associated with forms of conservation tillage can also help minimise compaction. Additional field traffic required by intensive tillage compounds the problem by breaking down soil structure. The combined physical and biological benefits of SOM can minimise the affect of traffic compaction and result in improved soil tilth.

Maintenance of SOM contributes to the formation and stabilisation of soil structure. Another spoke in the wagon wheel of environmental quality is improved soil tilth, structure and aggregate stability, enhancing the gas exchange properties and aeration required for nutrient cycling (Chaney and Swift, 1975). Critical management of soil airflow with improved soil tilth and structure is required for optimum plant function and nutrient cycling. It is the combination of many little factors rather than one single factor that results in comprehensive environmental benefits from SOM management. The many attributes suggest new concepts on how we should manage the soil for the long-term aggregate stability and sustainability.

A secondary benefit of less tillage and increasing SOM is reduced air pollution. CO_2 is the final decomposition product of SOM and is released to the atmosphere. Research has shown that intensive tillage, particularly the mouldboard plough, releases large amounts of CO_2 as a result of physical release and enhanced biological oxidation (Reicosky *et al.*, 1995). With conservation tillage, crop residues are left more naturally on the surface to protect the soil and control the conversion of plant C to SOM and humus. Intensive tillage releases soil C to the atmosphere as CO_2 where it can combine with other gases to contribute to the greenhouse effect. Thus a combination of the economic benefits of conservation tillage through reduced labour requirements, time savings, reduced machinery costs and fuel savings, combined with the environmental benefits listed above has universal appeal.

Indirect measures of social benefits as society enjoys a higher quality of life from environmental quality enhancement will be difficult to quantify. CA, using direct seeding techniques, can benefit society and can be viewed as both "feeding and greening" the world for global sustainability.

Limits of no-till for Carbon sequestration

Carbon sequestration through continuous CA is only a short-term solution to the problem of global warming. The amount of C that can be stored in the soil using no-till techniques will plateau in 25 to 50 years (Lal *et al.*, 1998). The time period depends on the specific geographic site, soil and climate parameters, and cropping practices that are followed. At some point a new equilibrium will be reached where there is no further gain in soil C; however, the environmental benefits will continue. In the long term, reducing CO_2 emissions from the burning of fossil fuels by developing alternate energy sources is the only solution. Soil C sequestration and potential associated C credit trading will allow major CO_2 emitters time to reduce their emissions, while developing economical long-term solutions. For the next 50 years, however, soil C sequestration can be a cost-effective option that buys society time in which to develop alternate energy options while still providing numerous environmental benefits.

Agricultural policy should play a prominent role in agro-environmental instruments to support a sustainable development of rural areas and respond to society's increasing demand for environmental services. Environmental protection and nature conservation require enhanced management skills that create extra work and cost for the farmers, but in no other sector can so much be achieved for the environment with so little input. We must no longer take for granted the contribution made to society by farmers through environmental measures but must compensate them appropriately through stewardship payments. Farmers using conservation techniques stand to gain from protecting the environment because it is in their fundamental economic interest to conserve natural resources for the future. It is in all our economic interests to have healthy and sustainable ecosystems to enhance our quality of life. The true economic benefits can only be determined when we assign monetary values to externalities of environmental quality. It makes more economic sense to take account of nature conservation from the outset than to have to repair damage after it is done, and in many cases the repair may not even be possible. CA without intensive tillage can play a major role in sequestering soil C and providing long-term global economic and environmental benefits.

CA with enhanced soil C management is a win-win strategy. Agriculture wins with improved food and fibre production systems, and sustainability. Society wins because of the enhanced environmental quality. The environment wins as improvements in soil, air and water quality are all enhanced with increased amounts of soil C. The win-win scenario will increase productivity, improve soil quality, and mitigate the greenhouse effect with major impact on our future quality of life.

References

Angers, D. A. and Simard, R. R. (1986). Relationships between organic matter content and soil bulk density. Relations entre la teneur en matiere organique et la masse volumique apparente du sol. *Canadian Journal of Soil Science Revue Canadian Science Sol.* **66**: 743–746.

Avnimelech, Y. and Cohen, A. (1988). On the use of organic manures for amendment of compacted clay soils: effects of aerobic and anaerobic conditions. *Biological Wastes* **29**: 331–339.

Chaney, K. and Swift, R. S. (1984). The influence of organic matter on aggregate stability in some British soils. *Journal of Soil Science* **35**: 223–230.

Braverman, M.P.; Dusky, J. A.; Locascio, S. J. and Hornsby, A. G. (1990). Sorption and degradation of thiobencarb in three Florida soils. *Weed Science* **38(6)**: 583–588.

Crovetto, C. (1996). Stubble over the soil: The vital role of plant residue in soil management to improve soil quality. *American Society of Agronomy*, Madison, WI. 245 p.

Davidson, E.A. and Ackerman, I. L. (1993). Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry* **20**: 161–193.

Edwards, W. M.; Shipitalo, M. J. and Norton, L. D. (1988). Contribution of macroporosity to infiltration into a continuous corn no-tilled watershed: Implications for contaminant movement. *Journal of Contaminant Hydrology* **3**: 193–205.

Grovers, G.; Vandaele, K.; Desmet, P. J. J.; Poesen, J. and Bunte, K. (1994). The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science* **45**: 469–478.

Houghton, R.A.; Hackler, J. L. and Lawrence, K. T. (1999). The U.S. carbon budget: contributions from land-use change. *Science* **285**: 574–577.

Hudson, B. D. (1994). Soil organic matter and available water capacity. *Journal of Soil and Water Conservation* **49(2)**: 189–194.

Lal, R. (2000). A modest proposal for the year 2001: we can control greenhouse gases in the world ... with proper soil management. *Journal of Soil and Water Conservation* **55(4)**: 429–433.

Lal, R.; Kimble, J. M.; Follet, R. F. and Cole, V. (1998). *Potential of U.S. Cropland for Carbon Sequestration and Greenhouse Effect Mitigation.* UDSA-NRCS, Washington, D.C. Ann Arbor Press, Chelsea, MI.

Le Bissonnais, Y. (1990). Experimental study and modelling of soil surface crusting processes. p. 13–28 **In:** Bryan, R.B. (Ed) *Soil erosion: Experiments and models,*. Catena Verlag: Cremlingen-Destedt.

Lee, K.E. (1985). *Earthworms: Their ecology and relationship with soils and land use.* New York: Academic Press. 411 p.

Lindstrom, M. J.; Nelson, W. W. and Schumacher, T. E. (1992). Quantifying tillage erosion rates due to moldboard plowing. *Soil and Tillage Research* **24**: 243–255.

Lobb, D. A. and Kachanoski, R. G. (1999). Modelling tillage translocation using steppe, near plateau, and exponential functions. *Soil and Tillage Research* **51**: 261–277.

Lobb, D. A.; Kachanoski, R. J. and Miller, M. H. (1995). Tillage translocation and tillage erosion on shoulder slope landscape positions measured using 137 Cesium as a tracer. *Canadian Journal of Soil Science* **75**: 211–218.

Papendick, R. I.; McCool, D. K. and Krauss, H. A. (1983). Soil conservation: Pacific Northwest. **In:** Dregne, H.E. and Willis, W.O. (Eds) *Dryland Agriculture.* Agronomy 23. ASA, Madison, WI.

Poesen, J.; Wesenael, B.; Govers, G.; Martinez-Fernadez, J.; Desmet, B.; Vandaele, K.; Quine, T. and Degraer, G. (1997). Patterns of rock fragment cover generated by tillage erosion. *Geomorphology.* **18**: 193–197.

Reicosky, D. C. (1998). Strip tillage methods: Impact on soil and air quality. p. 56–60. **In:** Mulvey, P. (Ed). *Environmental benefits of soil management.* Proceedings of ASSSI National Soils Conference, Brisbane, Australia.

Reicosky, D. C. (1997). Tillage-induced CO_2 emission from soil. *Nutrient Cycling in Agroecosystems* **49**: 273–285.

Reicosky, D. C.; Kemper, W. D.; Langdale, G. W.; Douglas Jr, C. W. and Rasmussen, P. E. (1995). Soil organic matter changes resulting from tillage and biomass production. *Journal of Soil and Water Conservation* **50**: 253–261.

Reicosky, D. C. and Lindstrom, M. J. (1993). Fall tillage method: effect on short-term carbon dioxide flux from soil. *Agronomy Journal* **85**: 1237–1243.

Reicosky, D.C. and Lindstrom, M. J. (1995). Impact of fall tillage and short-term carbon dioxide flux. p. 177–187 **In:** Lal, R. (Ed). *Soil and Global Change.* Chelsea, MI: Lewis Publishers.

Robert, M. (1996). Aluminum toxicity a major stress for microbes in the environment. p. 227–242. **In:** Huang, P.M. (Ed). *Environmental Impact.* Vol. 2, Soil component interactions. CRC press.

Robert, M. (2001). *Carbon Sequestration in Soils: Proposals for land management.* AGLL, FAO, United Nations, Rome. Report No. XXX. 69 p.

Schlesinger, W. H. (1985). Changes in soil carbon storage and associated properties with disturbance and recovery. p. 194–220. **In:** Trabalha, J.R. and Reichle, D.E. (Eds). *The changing carbon cycle: A global analysis.* New York: Springer Verlag.

Schumacher, T. E.; Lindstrom, M. J.; Schumacher, J. A. and Lemme, G. D. (1999). Modelling spatial variation and productivity due to tillage and water erosion. *Soil Tillage Research.* **51**: 331–339.

Skidmore, E. L.; Kumar, M. and Larson, W. E. (1979). Crop residue management for wind erosion control in the Great Plains. *Journal of Soil and Water Conservation* **34**: 90–94.

Soane, B. D. (1990). The role of organic matter in the soil compactibility: A review of some practical aspects. *Soil and Tillage Research* **16**: 179–202.

Tebregge, F. and Guring, R. A. (1999). Reducing tillage intensity – a review of results from a long-term study in Germany. *Soil and Tillage Research* **53**: 15–28.

Uri, N. D. (1999). Conservation Tillage in U.S. Agriculture. p. 130 **In:** *Environmental, Economic, and Policy Issues.* Binghamton, NY: The Haworth Press, Inc.